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ESTIMATION OF DATA-TRANSFER RATE FROM ONLINE GAMMA-RAY MONITORING PERFORMED BY SMALL-SATELLITE SWARMS IN NEAR SPACE

IVAN ILIEV[1,2], PLAMEN DANKOV[1]

[1]*Sofia University "St. Kliment Ohridski", Faculty of Physics, Department of Radio-Physics and Electronics, J. Bourchier blvd. 5, 1164-Sofia, Bulgaria*
[2]*Thetaconsult Ltd., J. Bourchier blvd. 5A, 1164-Sofia, Bulgaria*

Иван Илиев, Пламен Данков, ОЦЕНКА НА СКОРОСТТА НА ПРЕДАВАНЕ НА ДАННИ ПРИ МОНИТОРИНГ В РЕАЛНО ВРЕМЕ НА КОСМИЧЕСКО ГАМА ЛЪЧЕНИЕ, РЕАЛИЗИРАНО ОТ РОЯЦИ ОТ МАЛКИ СПЪТНИЦИ В БЛИЗКИЯ КОСМОС

В работата е формулирана идея за непрекъснат мониторинг на интензитета и спектъра на високоенергийно гама лъчение от далечния космос, изпълнен като вторична мисия с помощта на рояци от малки спътници от близкия космос, чиято първична мисия е посветена на доставка на широколентов интернет по съвременна 5G технология към базирани на Земята потребители. За тази цел всеки спътник от рояка трябва да бъде допълнително екипиран с ефективен, лек и евтин гама детектор с ниска енергийна консумация. Разгледана е технологията за събиране на данни при такъв непрекъснат мониторинг и е оценено количеството допълнителни данни от подобно приложение в гама астрономията на спътникови рояци за целите на онлайн картографиране на гама лъчението върху звездната карта, наблюдавана от Земята. Дискутирани са подходящите честотни обхвати, антенни системи и технологията на комуникационните сесии и е представен енергиен баланс на връзката от LEO орбити между 700 до 1500 km.

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In this work, we formulate an idea for continuous monitoring of intensity and spectra of high-energy gamma radiation from the deep space performed as a secondary mission by small-satellite swarms in the near space, which primary mission has been dedicated to broadband Internet delivery by modern 5G technology for ground-based users. For this purpose, each satellite has to be additionally equipped by low-cost, low-weight, low power-consumption, but enough effective gamma-ray detector. The technology for collecting of such data during the continuous monitoring has been explored and the needed additional data-transfer throughput from this gamma-ray astronomy application of the satellite swarms has been evaluated for the purpose of online mapping of this radiation over the star map observed by the Earth. Appropriate frequency bands, antenna systems, and communication sessions technology have been discussed, and simple satellite-Earth link budget for LEO orbits between 700 and 1500 km has been performed.

Keywords: gamma-ray spectroscopy, small satellites, data-rate throughput, link budget
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For contact / За контакти: Ivan I. Iliev, Theta-Consult Ltd., 5A, J. Bourchier blvd, 1164-Sofia, Bulgaria, i.iliev@thetaconsult.com; Plamen I. Dankov, Sofia University "St. Kliment Ohridski", Faculty of Physics, *J. Bourchier blvd. 5, 1164-Sofia, Bulgaria*; dankov@phys.uni-sofia.bg

1. INTRODUCTION

The ionizing radiation in the near space is different from the kinds of radiation existing on the Earth, such as X rays or gamma rays. The radiation on the Earth is mainly connected with the radioactive background (rocks, water basins, groundwater, Sun radiation, etc.), industrial radionuclide sources and radioactive contaminations with important influence over the human health. Contrariwise, space ionizing radiation consists of three other radiation kinds: particles trapped in the Earth's magnetic field; particles shot into space during solar flares (solar particle events), and galactic cosmic rays, which are high-energy protons (rarely photons), and heavy ions from outside our solar system. The possible secondary radiation from the Earth surface in the near space could be neglected due to the $1/d^2$ attenuation of the radiation power at distance d. A major part of the investigations of space ionizing radiation has been again connected with the human health issues and its influence on the astronauts in the spacecraft onboard as on LEO's (low-Earth orbits) (for example, on the ISS; International Space Station; not so strong), as well as beyond LEO's orbits during multi-year missions (as for astronauts travelling on a protracted voyage to Mars [1]; very strong). There exist many projects for space radiobiological research that deal with the understanding the nature of the space radiation environment and how radiation risks influence mission planning, timelines and operational decisions. These investigations will definitely more precisely elucidate the effects of space radiation on human physiology and aid in developing personalized radiological countermeasures for astronauts. Nowadays, the first "human radio-resistance roadmap" for space exploration has been developed [2].

The local space measurements of the ionizing radioactive radiation in the space are connected also with another important technical problem – the influence of this ionizing radiation over the commercial-off-the-shelf (COTS) components, embedded in the modern lean (risk) small satellites [3]. The small spacecraft (with payload less than 100-150 kg) have been already well developed for low-cost near-space missions (Earth observations and remote sensing, new space technologies' verifications, specific science missions, LEO communications for world-spread Internet connectivity, young people education, etc.), but now they have been seriously considered as candidates for a successful realization of low-cost deep space missions [4]. This has led to intense scrutiny over the radiation protection in small spacecraft, especially given their tendency to use COTS electronic and mechanic components, and development of radiation mitigation strategies for small spacecraft missions.

However, the investigation of the radiation in the space has a third very important aspect – observation of high-energy radiation from the deep space and development of space-based gamma-ray astronomy [5]. These observations already have a significant influence on the knowledge for the universe due to the fundamental character of the cosmic gamma rays and their spectra [6]. The physical processes that generate cosmic gamma rays can be summarized in four groups: collisions between high-energy particles (typically protons); collisions and annihilations between pairs of particle and antiparticle (e.g. electron and positron), undergoing radioactive decay of cosmic radioactive elements (their nuclei), and accelerated (typically by strong magnetic fields or by electrostatic fields in the nuclei) charged particles that radiate (the character of the radiation depends on the nature of the accelerating force in the space). Therefore, the astrophysical sources of cosmic gamma rays are quite different. The extreme physical conditions in the universe (e.g. in the nuclear-burning sites) produce a variety of excited radioactive nuclei [7]; thus allowing us to probe the unique physical environments of these objects, such as supernovae, neutron stars, black holes, etc. Gamma rays from radioactive decay are in the energy range from a few keV to ~8 MeV, corresponding to the typical energy levels in nuclei with reasonably long lifetimes (energy 1 MeV corresponds to a wavelength of about 10^{-12} m or a frequency of 10^{22} Hz). Another place that produces intensive gamma-ray radiation is the interstellar space, where the different types of collisions lead to excitations of nuclear levels, followed by de-excitation with accompanied characteristic gamma-ray line emission [8]. Such high-energy interactions also produce continuum gamma rays through the processes of inverse-Compton scattering, Bremsstrahlung, and other radiation processes related to an acceleration of charges in strong fields such as curvature radiation and synchrotron emission. The third important source is the annihilation of particles with their antiparticles, such as electron-positron annihilation, which results in a characteristic line at 511-keV energy from two-photon annihilation [9]. This characteristic gamma-ray emission has been mapped to occur in an extended region throughout the inner parts of our Galaxy.

Detection of the spectral signatures and continuum emission of the gamma rays allows intensive investigations as the big space objects (massive stars, Milky Way, other galaxies), as well as interstellar space, dark matter, etc. In gamma-ray astronomy, gamma-ray bursts (GRBs) are extremely energetic explosions that have been observed in distant galaxies. They are the brightest electromagnetic events known to occur in the universe – from ten ms up to several hours [10]. After an initial flash of gamma rays, a longer-lived "afterglow" is usually emitted at longer wavelengths (X-ray, ultraviolet, optical, infrared, microwave and radio frequencies).

All these considerations show that the gamma-ray monitoring in the space may have a strong impact on the human knowledge for the fundamental processes in the universe, on the stable behaviour of the space apparatus and technical equipment near to or far from the Earth and on the health and behaviour of the live organisms in the Space (including professionally-prepared astronauts) during short- and long-time missions. Of course, such global monitoring leads to accumulation of a huge amount of data for the detected gamma rays' intensity and spectra, which can be registered and digitalized in the detectors, transmitted from the satellites, received, collected, processed and classified on the Earth.

In this paper, we try to evaluate the possible volume of these digital data from the gamma-ray observation accumulated for a unit time and/or for a fixed period of time between two possible communication sessions from a single satellite, a constellation of satellites or satellite swarm to the corresponding Earth station or master satellite station (e.g. GEO satellite on geostationary orbit), where the collected data have to be sent. The satellites can send data from the payload detectors as through the telemetry channels, originally provided for the transfer of telemetry and command data for the satellite "health" on-orbit at relatively low data-rate speed, as well as through specially dedicated communication channels, where the data-rate speed could be considerably larger. In the last several years we indicate increasing efforts of the International Telecommunication Union (ITU) to recommend allocation of new higher-frequency bands for communication with small satellites for primary and secondary services [11] – in the X, Ku, K and Ka bands and beyond, which provides new possibilities for reliable data transfer from the LEO satellites to the ground stations' networks, already discussed in our paper [12]. Here we evaluate the possible data-transfer rate for the collected data from gamma-ray observation from a single satellite or from satellite swarms, applying different allocated frequency bands for Satellite-to-Earth downlink transfer, different antennas and different power transmit-receive modules. Based on the presented link budged between small-satellite swarms and ground stations at different LEO orbits between 700-1500 km we propose the implementation of gamma-rays monitoring in real-time performed by the future communication satellite swarms (e.g. like Starlink project) as their possible secondary mission and evaluate how the corresponding additional data transfer will influence the primary communication mission of these swarms.

2. MEASUREMENT OF GAMMA RADIATION IN THE SPACE AND GAMMA-RAY ASTRONOMY BY SMALL SATELLITES.

Observation of gamma rays became possible in the 1960s when effective detectors have been developed for such rare events as difficult to focus gamma-ray particles. Only very energetic gamma rays (with photon energies over ~30 GeV) can be detected by ground-based experiments because gamma rays coming from space are absorbed in the Earth's atmosphere. In fact, the gamma-ray astronomy became more efficient and with higher resolution mainly by the help of detectors placed above most of the Earth atmosphere (using stratospheric balloons and rockets) or the whole atmosphere (using spacecraft).

There exist many large and medium (probing) concept missions for more effective development of gamma-ray astronomy by space-based equipment, starting with the first gamma-ray telescope carried into orbit, on the Explorer 11 satellite in 1961, picked up fewer than 100 cosmic gamma-ray photons, which appeared to come from all directions in the universe that implying some sort of uniform "gamma-ray background". The first experiments with selected gamma-ray sources, the Sun flares with strong 2.223-MeV line (resulting from the formation of deuterium via the union of a neutron and proton), have been performed by OSO 3 (1967; 621 cosmic gamma-ray events), OSO 7 (1971) Orbiting Solar Observatories, and the Solar Maximum Mission (1980). Today such Sun-radiation observations are very important for prediction of the space weather around the Earth and in the rest of the solar system. These first space-based experiments confirmed the earlier findings of the gamma-ray background, produced the first detailed map of the sky at gamma-ray wavelengths, and detected a number of point sources. However, the resolution of the instruments was insufficient to identify most of these point sources with specific visible stars or stellar systems. In this period (the late 1960s and early 1970s) were detected the first unidentified GRBs from the deep space (probably hypernova explosions creating black holes) – by specially-equipped (constellation of) military defence satellites (Vela satellite series), and new scientific instruments on-board of satellites and space probes (mid-1980s), including Soviet Venera spacecraft and the Pioneer Venus Orbiter.

During its High Energy Astronomy Observatory program in 1977, NASA announced plans to build a "great observatory" for gamma-ray astronomy Compton Gamma Ray Observatory (CGRO, launched in 1991, de-orbited 2000) based on advanced detector technology [13]. This gamma-ray telescope carried four major instruments, which have greatly improved the spatial and temporal resolution of gamma-ray observations. The CGRO provided large amounts of data, which are being used to improve our understanding of the high-energy processes in our universe.

Currently, the main space-based modern gamma-ray observatories are [6]: INTEGRAL (International Gamma-Ray Astrophysics Laboratory, launched 2002 as an ESA mission), FERMI (launched by NASA in 2008), and AGILE (all-Italian Astro-rivelatore Gamma a Immagini Leggero, launched in 2007). They are large well-equipped gamma-ray observation instruments; for example, FERMI includes LAT, the Large Area Telescope, and GBM, the Gamma-Ray Burst Monitor, for studying gamma-ray bursts [5]. One of the most important observations in Nov. 2010 by the FERMI Gamma-ray Space Telescope was the two detected gigantic gamma-ray bubbles, spanning about 25000 light-years across. These bubbles of high-energy radiation are suspected as erupting from a massive black hole or evidence of a burst of star formations from millions of years ago. The formations were discovered after filtering out "fog of background gamma-rays". This discovery confirmed previous clues that a large unknown "structure" was in the centre of the Milky Way [14].

The considered modern gamma-ray telescopes are really very efficient; for example in 2011 the FERMI team released a catalogue of gamma-ray sources detected by the satellite's LAT, which produced an inventory of 1873 objects shining with the highest-energy form of light. 57% of the sources are blazars (an active galactic nucleus with relativistic jet composed of ionized matter travelling at nearly the speed of light and directed very nearly towards Earth). Over half of the sources are active galaxies, their central black holes created gamma-ray emissions detected by the LAT. One-third of the sources have not been detected in other wavelengths [15]. Last year (in April 2018), the largest catalogue of high-energy gamma-ray sources in space was published [16]. In 2017, for the first time, a connection between high-energy gamma-ray bursts and solar eruptions from the far Sun side was established by the Fermi Space Telescope and NASAs Solar Terrestrial Relations Observatory (STEREO) spacecraft, which is a very important source of information. One prominent mechanism is thought to be proton collisions that result in a particle called a pion, which quickly decays into gamma rays [17].

In the last several years the measurements of gamma rays from the space and gamma-ray astronomy received a new very strong support – utilization of CubeSats with incorporated gamma-ray detectors and deployed as space-based telescopes. They are small satellites built in standard unit sizes and form factors (1U, 2U, 3U,…6U,…12U,…24U,…; 1U = 10 cm × 10 cm × 10 cm cube with typical weight 1-2 kg), which have been growing in popularity for low-cost Earth observations and remote sensing, a new generation of communications, interesting and valuable science missions and project-orientated student education, but have been ignored so far within the field of astronomy [18]. The CubeSat has an important advantage as a space-based tool like the most other key devices in the everyday human live today – smartphones, optical cameras, drones, laptops, etc. – they can effectively incorporate in the spacecraft structure, electronics, power systems, onboard computer and communications modules new innovative, standardized and miniaturized COTS components with continuously improving technical parameters at progressively decreasing prices.

The CubeSats can fill several key gaps in astronomical research and enable science experiments, which are not fully possible with the existing large space missions considered above. It is a known fact that the capacity, energy resources and time schedule of the flagship space telescopes must be shared between many science programs and onboard instruments and these expensive science instruments are really extremely busy and definitely similar single instruments cannot register all possible changes in the deep-space radiation. In the same time the perspective small gamma-ray telescopes, based on CubeSats, can monitor selected sources for enough long time (e.g., weeks or months). Moreover, the dedicated for gamma-ray detection CubeSats may also pair with the large space- and ground-based instruments to provide complementary data to better explain the physical processes observed. Currently, the developed science missions for CubeSats include a wide variety of astrophysical experiments, including exoplanets, stars, black holes and radio transients. The high-impact astronomical research with CubeSats is possible due to three important feasibilities, based on advances in technologies, namely precision pointing (e.g. 5-15 angle seconds pointing stability for several minutes' observation), compact sensitive detectors (considered in the next section) and incorporated miniature propulsion systems.

Several small observatories housed in CubeSats and primarily prepared for astronomical research have been presented in [18]. The ASTERIA (Arcsecond Space Telescope Enabling Research in Astrophysics) is a 6U CubeSat [19], led by the Jet Propulsion Laboratory (JPL) and the Massachusetts Institute of Technology (launched in August 2017). This is one of the first CubeSats instrument enabled for astronomical measurements of exoplanetary transits across bright stars with <100 ppm photometry. This small space-based telescope has two advance capabilities for astronomy: 5-second pointing stability over a 20-minute observation and mK-level temperature stability of the imaging detector. Another 6U CubeSat, the Colorado Ultraviolet Transit Experiment (CUTE), led by the University of Colorado Boulder and NASA (planned for launch in the first half of 2020) has goals to conduct a survey of exoplanet transit spectroscopy in the near-UV of a dozen short-period, large planets orbiting FGK stars to constrain stellar variability and measure mass-loss rates [20]. The 3U CubeSat PicSat, a French-led supported primarily by the European Research Council (launched at polar orbit in January 2018) has a goal to observe in visible light the potential transit of the directly-imaged giant planet β Pictoris b, and even its moons and debris [20]. The HaloSat, a 6U CubeSat led by the University of Iowa and NASA has aims to measure the soft X-ray emission from the hot halo of the Milky Way galaxy to resolve the missing baryon problem, in which the number of baryons observed in the local universe is about half the amount recorded by the cosmic microwave background [21]. A 6U CubeSat, Star-Planet Activity Research CubeSat (SPARCS), led by Arizona State University and NASA [22] (late-2021 launch to a sun-synchronous orbit), is devoted to the far- and near-UV monitoring of low-mass stars (0.2–0.6 $M_{\odot}$), the most dominant hosts of exoplanets. The stellar UV radiation from *M* dwarfs is strong and highly variable and impacts planetary atmospheric loss, composition and habitability. The SPARCS will spend an entire month on each of at least a dozen *M* stars measuring rotational variability and flaring in both bands to be used as inputs to the stellar atmosphere and planetary photochemistry models. The BurstCube, a 6U CubeSat, led by the NASA's Goddard Space Flight Center (2021 launch) is dedicated to detecting gamma-ray transients by four CsI detectors from 10 keV to 1 MeV energy range. Its fast reaction time and small localization error are a valuable capability to catch the predicted counterparts of gravitational wave sources [24], complementing existing facilities such as FERMI. The BurstCube will autonomously detect GRBs on-board, rapidly downlinking data for timing and localizations that are disseminated to ground-based observers to maximize the chances of detecting afterglows. BurstCube will increase the rate of concurrently detected GRBs and gravitational waves by enhancing the sky coverage beyond current sensitive instruments. The team aim is to create a constellation of ten BurstCubes to provide all-sky coverage at significantly less cost than the typical large mission.

The considered selected examples above clearly show that the CubeSat-based gamma-ray instruments have a significant future in the modern gamma-ray astronomy even working as single satellite telescopes. If the same gamma-ray observation missions have been developed in an extended option for working in a constellation of small satellites on synchronized orbits operating together under shared control in concert, or for satellite swarms, flying in formations with relatively close proximity with individual behaviour and “swarm intelligence”, the effectiveness and area of coverage of the gamma-ray observations in the space will increase considerably. We will consider below these options in the frame of data collection and data throughput of possible gamma-ray events for a selected time interval, collected by formations with a large number of satellites.

However, let’s first present an example for innovative synchronized application of users' smartphones for ultra-high energy cosmic rays (UHECRs) with energy above 10^{18} eV on the Earth surface. It is proposed in [25] a novel approach for observing UHECRs by repurposing the existing network of smartphones as a ground detector array. Extensive air showers, generated by cosmic rays, produce secondary particles like muons and high-energy photons, which can be detected by the CMOS sensors of smartphone cameras. A key moment of this proposal is the fact that the small size and low efficiency of each sensor can be compensated by a large number of active phones. The authors have shown that if user adoption targets are met, such a network will have significant observing power at the highest energies. Thus, the detector in the sensitive to UHECRs smartphone is the ordinary camera, a CMOS device in which silicon photodiode pixels produce electron-hole pairs when struck by visible photons. These devices are designed to have reasonable quantum efficiency for visible light, and the same principle allows the sensor to detect high-energy photons as well as minimally-ionizing particles such as muons. An application running on the smartphone has access to an array of pixel response values, commonly with 8-bit precision. Though many stages of processing occur between the direct measure of the deposited energy by the CMOS sensor and the delivery of pixel response values, the last value is a reasonable proxy for the detected UHECR.

The investigated events are very rare; it would be possible to detect approximately one event every 100 years in a surface area of 1 km^2. The CRAYFIS project [26] proposes using a distributed mobile phone network to detect these UHECRs applying an algorithm for constructing convolutional neural networks that can be used with conventional mobile phones to record the UHECRs with technology similar to that in particle detectors. The secondary air particles interact with the CMOS camera and leave traces of weakly activated pixels, which can be difficult to distinguish from interference and random noise. Experiment volunteers have to install the application on their smartphones and to leave them with the cameras facing down overnight so that normal light wouldn't fall on them. Smartphones scan “empty” megapixel images at a speed of 5 to 15 frames per second and send the necessary information to the server for offline shower reconstruction; most events are between 50 and 200 bytes of data. It is expected signals from the interaction of cosmic rays to occur in fewer than one out of 500 image frames. Due to the fact that millions of phones will potentially participate in the experiment, a problem arises in separating those images on which muon tracks are recorded from all the others. A trigger algorithm (15-30 Hz repetition frequency) is required to eliminate background noise data. It is created a neural network for the detection of secondary muon signals, which can be used on any mobile phone fast enough to process a video stream. A special feature makes it possible to use the algorithm on something as simple as a mobile phone, meaning that they can now analyze responses to cosmic rays.

The presented CRAYFIS project [26] is an indicative example how a network of non-scientific members using devices with other primary application can help for valuable scientific investigation of such rare events of gamma-ray radiation following the forming of supernovae and black holes in the universe by applying of very simple detectors of the secondary particles produced in the Earth atmosphere by ultra-high energy cosmic rays and a typical 5G technology to collect and post-process data from thousands of ground-based sensors.

Our idea is to propose a transfer of such technology in the near space for massive more effective gamma-ray observations at lower energies by already existing on-orbit small satellite swarms. Fortunatelly in the last years several perspective projects appear for broadband Internet connectivity from the near space (300-1500 km) by the help of large formations of satellites, which are very suitable for gamma-ray observation as a secondary function. What do we mean?

The deployment of thousands of small satellites at LEO orbits for massive coordinated gamma-ray bursts observation as a primary goal is not so realistic due to many reasons. Similar populations of many low-cost, high-performance satellites as big swarms are economically promising and justified at the moment only for the realization of the new 5G commutation technologies for global coverage of the whole Earth surface with millions of customers by new space-based Internet communication systems. Let's consider the existing projects.

The first report for a potential involvement of Google Inc. in offering broadband Internet services was dated February 2014 [27, 28] and based on a very large constellation of 1600 satellites. By June 2014, WorldVu (later renamed as OneWeb [29]) had acquired the satellite spectrum that was formerly owned by SkyBridge, in a much earlier attempt to offer broadband Internet services via satellites. Now the OneWeb project is based on deployment of an initial 650-satellite constellation currently being built out to provide global satellite Internet broadband services to people everywhere and is on track to provide global services starting in 2021. The first six satellites of the constellation were launched in February 2019 [30] and the satellite system is planned to be fully online by 2027 (they are being built by OneWeb Satellites, a joint venture between Airbus and OneWeb). The satellites will operate in 18 circular LEO orbits at ~1200 km altitude, transmitting and receiving in the Ku band (12-18 GHz). OneWeb is considering nearly quadrupling the size of the satellite constellation over time by adding 1972 additional satellites. The satellites of OneWeb constellation are ~150 kg. They use a technique called "progressive pitch", in which the satellites are slightly turned to avoid interference with Ku-band satellites in GEO orbit. The user terminal antenna on the ground will be a phased array antenna 36×16 cm and will provide Internet access at 50 Mbps downlink (almost certainly less uplink). The satellites have been designed to comply with "orbital debris-mitigation guidelines for removing satellites from orbit and, for LEO satellites, assuring that they re-enter the Earth's atmosphere within 25 years of retirement" [31].

Another even more ambitious project is the Starlink project as a large LEO satellite constellation developed by American company SpaceX [32] to start (in 2020) a massive delivery of broadband Internet at speed more than 7 Gbps up to 40 million customer ground-based transceivers (in 2025) [33]. The reasons to attract our attention to consider this project applicable for massive gamma-ray observation as a secondary function by the whole swarm is the fact that the used satellites are enough universal; the SpaceX plans to sell satellites that use a satellite bus applicable for military, scientific or exploratory purposes [34]. The Starlink constellation will consist of almost 12000 satellites (6 times more than the operational spacecraft in Earth orbits today) (now even planed 42000!) in three orbital shells and 82 orbits. The deployment of these satellites will be ready by the mid-2020s: initially placing approximately 1600 satellites at 550-km altitude, subsequently placing ~2800 Ku- and Ka-band (26.5-40 GHz) satellites at 1150-km altitude and ~7500 V-band (57-71 GHz) satellites at 340 km [35]. The first 62 satellites have been already launched [35] – see also Fig. 1. The low-cost satellites of 100-to-500 kg mass (227 kg at 550-km orbit) will form typical large satellite swarms at the considered 3 orbital belts. Swarms of miniature satellites are cheap and quick to deploy. Thousands of them could be released from a large central satellite in orbit. Swarm members are able to receive and send signals and to perform basic logic operations. Having swarm intelligence they could be combined in clusters of fewer, more-complicated and manoeuvrable formations that act as communications or analysis hubs (like considered by us small satellite swarms for intelligent debris aggregation; see [37, 38]). The Starlink satellites will employ optical inter-satellite links (at frequency >10 THz), phased array

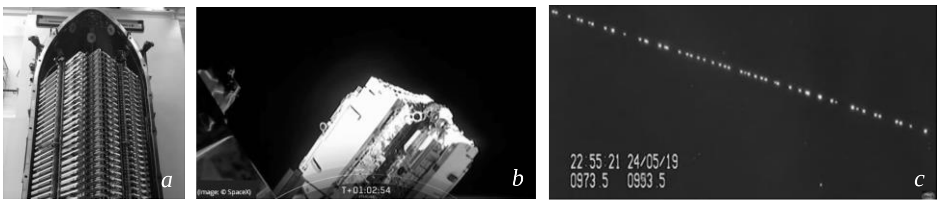

Figure 1. Starlink satellites [35, 36]: *a*) in stacked configuration on the reusable rocket Falcon 9; *b*) moment of the single satellite deployment; *c*) photography of the satellite's track before satellites to raise the selected orbit.

beam-forming (> 24 GHz) and digital processing technologies in the Ku and Ka bands for data downlink, according to documents filed with the U.S. Federal Communications Commission (FCC). This will ensure a relatively big data-transfer rate. The Starlink satellites use Hall-effect thrusters with krypton gas as the reaction mass for orbit raising and attitude control and therefore, each satellite will have enough manoeuvring and orientation capabilities.

There exists also other projects and companies (excepting already considered OneWeb and SpaceX), which plan to launch big broadband LEO constellations: Amazon (3236 satellites in the next decade; project Kuiper), Samsung (4600-satellite constellation orbiting at 1400 km), Canadian Telesat (world's first 5G backhaul demo over LEO satellites), etc. However, we selected to discuss our concept for possibilities for implementation of massive gamma-ray observation on the base of Starlink satellite swarm at 1150-km altitude.

3. GAMMA-RAY SENSORS FOR SMALL SATELLITES.

The detectors for gamma-ray spectrometry in the 100 keV to GeV range could be based on scintillators, solid-state detectors, drift or time projection chambers, and trackers made up of spark chambers or solid-state detector stacks [6]. The physical challenge is to produce a cascade of inelastic interactions of the primary photon and its secondaries within the volume of the detector and to produce an electrical signal which is proportional to the total energy deposit of the cascade. High levels of background radiation lead to detectors which respond quickly and have short dead times.

The scintillation detectors have an advantage. The issue with scintillation detectors is to ensure a homogeneous and linear light collection over the volume of the scintillation detector. Imperfections result in different signal amplitudes per energy deposit, depending on the location of interactions within the detector volume. Inorganic scintillation crystals (e.g. $LaBr_3$) stay efficient solutions for energy measurement in gamma-ray experiments above 10 MeV because they can be implemented in large quantities and volumes (e.g. recently in FERMI). Plastic scintillators are also widely used as active shielding in high-energy experiments for background particle detection and rejection.

The spectral resolution required for the identification of gamma-ray lines and relating them to specific nuclear transitions practically can only be achieved through solid-state detectors (Si, Ge, CdTe, CdZnTe) [40]. Solid-state detectors operate through a collection of the charge liberated from photon interactions as electrons are activated into the conduction band. In semiconductor detectors, a small bandgap of few eV only allows very sensitive high-resolution detectors. Germanium detectors have been established as standard in terrestrial nuclear-physics experiments, and also space-borne cosmic gamma-ray experiments. In recent years, CdZnTl detectors have become popular, because they can be operated at room temperature, rather than the cryogenic temperatures required for Ge detectors, at a nearly similar performance.

There exist several publications describing gamma-ray detectors and spectrometers, specially developed for CubeSat applications [41-44]; most of them can be considered as flight-proven components. The choice of the detector type and geometry for incorporation in CubSats depends on performance requirements (energy range, detection efficiency, detection area, spatial resolution, spectral and time resolution) and allocated resources, which are usually very limited in the small satellites (10 to 100 W electrical power, 10 to 100 kg mass budget, 0.1 to 1 Mbit per day telemetry downlink for a typical instrument). In addition to semiconductor detector properties, the space environment has to be taken into account to design all subsystems of an instrument. The whole gamma-ray detector includes the sensor part, which usually has to be temperature stabilized, the front-end electronics with mixed components (analog front-end channels with charge sensitive preamplifier, first filtering stage and digital electronics for readout control, signal sampling; the electronic noise performance is sensitive to the detector leakage current and the input capacitance and therefore the front-end electronics has to be optimized to the concrete sensor properties), the hybridization, i.e. optimized interconnections between the sensor and electronic pads and properly shielding (to stop X- and gamma rays out of the field of view) [40].

In our case, for incorporation in LEO small satellites as a secondary payload, the most important issues of the selected gamma-ray detectors are the small weight and sizes; low energy consumption, enough sensitivity, low dead time and degree of the accumulated data in Mbits between two communication sessions for downlink the results to the ground station or to the command centre.

Table 1 presents a comparison between some gamma-ray detectors.

Table 1. Comparison between some parameters of considered detectors [45]

No.	Type/material	Sizes, mm	Sensitivity, cps/μS/h (Cs-137)	Weight, g
1.	CsI	38 × ϕ13	210	40
2.	CZT	1000 mm^3	1000	60
3.	NaI	25 × ϕ25	290	120
4.	CsI+Li	38 × ϕ35	1500	550
5.	NaI	63 × ϕ63	4600	1400
6.	Organic scintillator	75 × ϕ75	5800	1400

4. EVALUATION OF THE REQUIRED COMMUNICATION LINE SPEED SERVING A GAMMA-SPECTROMETRIC SYSTEM BASED ON CsI (Tl) DETECTOR.

A gamma spectrometric system capable of georeferencing the measurement spectra should have a sufficiently fast communication line for transmitting coordinates, relative flight altitudes and accumulated spectrums over one period of integration. The most volumetric part of the data sent by the gamma-detecting system is the corresponding spectrum with a defined number of channels. This number depends on the applied multichannel analyzer (MCA), and the information in each channel is a positive integer, the maximum value of which depends on the expected maximum counting rate in one channel multiplied by the integration time. For computational convenience, the integration time is usually 1 s, which means that the accumulated number of pulses will be equal to the counting speed in [s^{-1}] or [cps]. The maximum number of pulses is determined by the system performance or, in particular, by the so-called “dead time”. The more channels there are in one spectrum, the narrower they will be, and the obtained spectrum will be closer to the continuous distribution. There must be no drastic difference between the numbers of pulses in two adjacent channels. To provide this in the full width at half maximum (FWHM) of a real peak, there must be at least 5 channels (i.e. FWHM = 5 channels) [46]. If we know the resolution of the detector used for certain energy, we can calculate the minimum number of channels according to this rule:

$$N_{total} = \frac{E_{\max} \times \mathrm{FWHM}}{E_0 \times R} \tag{1}$$

where:
N_{total} – total number of channels [channel];
E_{max} – maximal necessity energy in the spectrum [MeV];
FWHM – full width at half maximum; in our case equal to 5 channels;
E_0 – energy in the peak [MeV];
R – detector resolution in [%]

The number of channels can be reduced by ignoring the channels corresponding to the lowest energies. Radiation with such energies is largely absorbed by the detector shell, but more importantly, it is mainly in these channels that the noise of the electronics conceals the useful signal.

The required number of MCA channels can be determined by expression (1). For the selected CsI (Tl) detector we apply the catalogue resolution $R \approx 6\%$ for ^{137}Cs (662 keV) and a 0-10 MeV energy range. According to (1):

$$N_{total} = \frac{10 \times 5}{0.622 \times 0.06} = \frac{50}{0.03732} \approx 1340 \text{ channels} \tag{2}$$

That is, the MCA must have a minimum of 1340 channels or, in particular, the analog-to-digital converter (ADC) input must have at least 11 bit amplitude sampling equivalent to $2^{11} = 2048$ channels.

For the low energy range (<500 keV), where the noise of the electronics falls and the high count rate could overload the counter, a separate detector with a thinner foil window could be used. If the detector scintillator is the same, CsI (Tl), the number of channels for the low energy range will be 67, which means 6 bit ADC. As the processes generation, such photons are pretty fast it is valuable to reduce the integration time to about 0.063 s (or ~16 Hz repetition frequency). Each of the short spectrums should have its ID number inside the one second integration time. Its number would require an additional 4-bit record.

For the higher energy range, from 10 to 100 MeV, the detector sensitivity is very low and the integrated spectrum could have a reduced number of channels, just enough to keep rough information about the high energy photons. Reducing the required number of channels with a factor of 10, we can use second ADC with the same number of channels (2048 = 2^{11} =11 bit) for the high energy range.

For one integration period (1 s) we assume the maximum number of counts in one channel to be 8000 = 2^{13} = 13 bit. With the estimates of the required number of channels and number of channel pulses, we can calculate that the amount of memory required to record a spectrum would be:

$$4096 \times 13 \text{ bit} + 16 \times [(67 \times 13 \text{ bit}) + 4 \text{ bit}] = 67\,248 \text{ bit} \tag{3}$$

The second part of the necessary data sent by the detector system is the information required for positioning and the measurement time, serving as an identifier for each measurement, and preserving the order of reproduction. If the gamma-ray detector has been mounted on a satellite on LEO, it still can use GPS-navigation, which applies precise real-time kinematic (RTK) positioning; the 3D position accuracy is about 1-1.5 m [47]. This parameter depends on the accuracy requirements we set for the measurement and the desired resolution of the obtained gamma-ray map, which is our final goal. Under such requirements, we must use coordinates with the following length of the track:

DDMM.MMMMM(MM), DDDMM.MMMMM(MM)

(for example: 3404.7041778, 07044.3966270)

Thus, for the representation of the current time for a single measurement after the encoding of the form “hh:mm:ss”, 2×3×5×9×5×9 = 12150 ≈ 2^{14} = 14 bit would be sufficient and additional 20 bits for the date record. To write the coordinates in a form identical to their standard NMEA message (National Marine Electronics Association), such as DDMM.MMMMM, DDDMM.MMMMM requires ~85 bit. In the case of LEO, 1500000 meters ≈ 2^{24} = 24 bits are required to record a 1500-km altitude with an accuracy of 10 cm (as a low limit). Thus, the total required data speed for online data conversion is approximately:

$$67\,248 \text{ (for spectrum)} + 14 \text{ (time)} + 20 \text{ (date)} + 85 \text{ (coordinates)} + \\ + 24 \text{ (altitude)} = 67.391 \text{ kbps} = 8.423 \text{ kBps} \tag{4}$$

That is, the minimum data flow for a CsI (Tl) detector, with a maximum altitude of 1500 km ±10 cm, the precision of coordinates compatible with RTK GPS (1 cm as a low limit), maximum counting speed of 17 000 cps per keV (0-500 keV), 1100 cps per keV (0.5-10 MeV), 180 cps per keV (10-90 MeV) would be only 67.391 kbps (or ~100 kbps with 150-% margin). Of course, it is necessary to separate the packets from one another with service words (header) or to use ready communication protocols, which will increase the necessary flow. In all cases, we can consider a maximal data rate of ~160 kbps for a single gamma-ray system, which measures gamma radiation once per second, if the information has been transmitted continuously during the flight (e.g. as for UAV applications or LEO satellites in a swarm, applying inter-satellite connections). For a set of measurements 5-15 times per second (as in the project for gamma-ray observation by smartphones; or 16 times per second for measurements in the low energy range, <500 keV), the online data rate can increase up to 0.8-2.56 Mbps.

When the obtained information has to be stored in an external memory on satellite board for one or more orbital periods between two communication sessions from the satellite to the corresponding Earth station, the accumulated data will increase, e.g. the throughput for one 90-minute orbital period will be up to 864 Mb. The needed additional transmission speed downlink should be 2.4 Mbps for a 6-minute communication session. Now, if we consider gamma-ray observation by a satellite swarm when the ordinary (slave) swarm members communicate with one main (master) satellite from the swarm cluster, responsible for the data transmission to the Earth, the possible throughput due to the gamma-ray observation will depend on the number N_s of slave satellites in the cluster; e.g. the total throughput will increase by a factor $864.N_s$, Mb for one 90-minute orbital period, accumulated from N_s = 10-100 slave satellites in one cluster. In this case, the needed additional transmission downlink speed of a single master satellite should be $2.4.N_s$ Mbps for a 6-minute communication session, which already could be acceptable only after applying of specially dedicated communication link for separate gamma-ray data transfer through the master satellite. This is an example of how the small amount of data could be multiplied due to the mission organization reasons and a big number of sensors. In this case, preliminary post-processing of the raw gamma-ray spectrum should be performed on the place of each sensor to reduce the accumulated data throughput and a reliable synchronization by time and position between the slave satellites should be achieved on the base of the swarm intelligence principles.

In fact, the idea of using satellite swarms for high-speed Internet is to provide full-time connections, no matter of the single satellite position. Thanks to this the speed of the needed connection for online gamma astronomy observation would be no more than $160.N_g$ kbps, where N_g is the total number of the satellites carrying gamma-ray detectors on-board.

5. COMMUNICATION LINK BUDGET FOR ONLINE GAMMA-RAY OBSERVATION.

The daily data-transfer throughput is a key parameter for the realization of the communication function of the small satellites, as for a single satellite, as well as for a synchronized satellite swarm. It depends on many factors, but the most important of them are transmitted powers in the satellite and the ground station, P_{sat} (limited) and P_{GS}; allocated frequency bands and bandwidths (limited), antenna gain/directivity, antenna gain-over-temperature ratio (G/T), required digital modem input threshold E_b/N_0 (energy per one bit E_b over the system noise N_0), used modulation and coding schemes, lossless data compression, the access time for a single communication session with one Earth station (limited), number of the Earth stations (optional), etc. Let us evaluate this important parameter using a simple analysis [48]. First of all, the needed gross bit rate in dBbps can be determined by

$$R_b, \text{dBbps} = (C/N_0 - E_b/N_0 - \text{Margin}), \tag{5}$$

which allows the realization of maximal achievable bit rate $r_b, \text{bps} = 10^{R_b/10}$. The spectral density of the carrier-to-noise ratio C/N_0, dB.Hz is calculated by

$$C/N_0 = \text{EIRP}\big|_{Tx} + G/T\big|_{Rx} + 228.6 - \text{Losses} - \text{BO}, \tag{6}$$

where $\text{EIRP}\big|_{Tx} = G_{Tx} + P_{Tx}$ is the transmitter (Tx) equivalent isotropically-radiated power (EIRP), the receiver (Rx) $G/T\big|_{Rx}$ ratio (typically the noise temperature has been accepted T~290 K for the Uplink (UL) channel and T~30 K (the worst case) for the Downlink (DL) channel, BO is the input/output back-off (several dB; not taken into account here). The main part of the "Losses" is the free-space losses = $20\log(4\pi d/\lambda)$ (d – altitude); the other important part in our case is the antenna misalignment losses, but they can be taken into account using the actual antenna pattern. “Margin” depends on the used communication standard.

First of all, let’s select for the concrete analysis several communication bands, allocated by ITU for amateur-satellite services satellites for the downlink (DL) channels [49] (we don’t know whether the big satellite swarms for the future broadband Internet delivery will use exactly these channels, but they are most applicable for non-licensed purposes). The selected frequency bands for DL channels have been presented in the first column of Table 2 and the corresponding permitted bandwidth *BW* – in the second column, namely: 435-438 MHz, 2.40-2.45 GHz, 5.83-5.85 GHz, 10.45-10.5 GHz; 24-24.05 GHz. Part of these bands coincides with the free ISM (Industrial, Scientific, Medical) bands. We added also two wide allocated frequency bands 8.025-8.40 GHz and 25.5-27.0 GHz, assigned for EESS (Earth Exploration Satellite Services) space applications for DL channels. Table 2 presents also the results for the needed gross bit rate R_b in dBbps and maximal achievable bit rate r_b in Mbps for the selected bands with smaller effective bandwidth $BW_{eff} < BW$, reduced due to the Doppler shift on the selected LEO orbits 800/1500 km. We can see in Table 2 that the maximal achievable bit rate for pure QPSK modulation (without applying of any additional coding-gain or spread-spectrum techniques; they will additionally increase the bit rate) depends mainly on the permitted bandwidth and can reach values ~14-74 Mbps for BW_{eff} ~ 10-50 MHz (with appropriate coding these values can exceed 100 Mbps, as it is shown in [50]).

Another interesting question is the determination of the needed transmitted power P_{sat} of the satellite transmitters for the realization of downlink data transfer with a satisfactory bit-error rate (BER) less than 10^{-5} (again without applying any codding-gain techniques). Table 3 contains the results from this simple link

Table 2. Maximum achievable bit rate r_b, Mbps for QPSK modulation in an effective bandwidth BW_{eff} reduced due to the Doppler shift and needed gross bit rate R_b, dB.bps

Allocated frequency band, GHz	Max permitted BW, MHz	Max Doppler shift, kHz♣	Min effective BW_{eff}, MHz♣	Max bit rate r_b, Mbps (QPSK)♣	Needed gross bit rate R_b, dB.bps (QPSK)
0.435-0.438	0.02	±10.2/9.3	0.01/0.0011	0.03	44.77
2.427-2.443	10	±57.2/52.1	9.89/9.90	14.8/14.9	71.71
5.83-5.85	10	±101.9/92.8	9.70/9.73	14.5/14.6	71.65
10.37-10.45	10	±244.8/223.0	9.51/9/55	14.3/14.4	71.55
24.05-24.25	10	±568.1/517.6	8.86/8.96	13.3/13.4	71.28
8.025-8.175	50*	±191.5/174.5	49.62/49.65	74.4/74.5	78.72
25.50-27.00	50*	±632.6/576.3	48.73/48.84	73.1/73.3	78.65

* available channel bandwidth for EESS frequency bands; ♣ pair of parameters for 800/1500 km orbit altitudes

Table 3*a*. Available E_b/N_0 and margin M, dB in the Downlink (DL) channels for QPSK modulation and using single planar patch on-board antenna with fixed gain +7 dB and equivalent dish antenna with diameter 1.2 m for the ground station (P_{GS} = 2 W)

Central f, GHz / BW, MHz	LEO altitude, km	Path losses, dB♣	C/N_0, dB.Hz♣	Available E_b/N_0; Margin M, dB (P_{sat} = 1 W; P_{GS} = 2 W; 1.2-m diameter for the equivalent dish)♣	Req. P_{sat}, W (E_b/N_0 = 9.6 dB; M = 3.5 dB)♣
2.435/10	800/1500	158.2/163.7	89.3/86.84	(17.60;8.00)/(12.15;2.55)	0.355/1.25
5.84/10	800/1500	163.3/171.2	89.3/86.84	(17.65;8.05)/(12.22;2.63)	0.350/1.23
10.41/10	800/1500	170.9/176/3	89.3/86.84	(17.70;8.10)/(12.30;2.70)	0.346/1.22
8.10/50*	800/1500	168.7/174.1	89.3/86.84	(9.58;0.98)/(5.11; -4.49)	1.785/6.28

* available channel bandwidth for EESS frequency bands; ♣ pair of parameters for 800/1500 km orbit altitudes

Table 3*b*. Available E_b/N_0 and margin M, dB in the Downlink (DL) channels for QPSK modulation in the X band only (10.41 GHz/10 MHz) for different on-board antennas (P_{GS} = 4 W; equivalent dish antenna with diameter 1.8 m for the ground station)

On-board antennas	Antenna gain, dB / 3-dB beamwidth $\Delta\theta/\Delta\varphi$, deg	LEO altitude, km	C/N_0, dB.Hz♣	Available E_b/N_0; Margin M, dB (P_{GS} = 4 W; 1.8-m diameter for the equivalent dish)♣	Required P_{sat}, W (E_b/N_0 = 9.6 dB; M = 3.5 dB)♣
Single patch	+9.4/ 61.1/61.1	600/1500	97.6/ 89.7	(19.3; 9.7)/ (10.4; 0.8)	0.24/1.50
2-patch array	+12.7/ 27.5/61.1	600/1500	101.0/ 93.1	(22.7; 13.1)/ (14.8; 5.2)	0.107/0.68
4-patch linear array	+16/ 13.8/61.1	600/1500	104.3/ 96.4	(26.0; 16.4)/ (18.1; 8.5)	0.051/0.317
2x2-patch array	+12.9/ 27.1/27.1	600/1500	101.2/ 93.2	(22.9; 13.3)/ (15.0; 5.4)	0.104/0.65

♣ pair of parameters for 600/1500 km orbit altitudes

budget for different cases: for a single patch onboard antenna – Table 3*a*, and for antenna arrays – Table 3*b*), which are presented in two options: values of the available E_b/N_0 and the corresponding margin M for fixed powers $P_{sat,\ GS}$, and vice versa, the required powers P_{sat} for a fixed threshold of E_b/N_0 = 9.6 dB and margin M = 3.5 dB for two typical LEO altitudes 800 and 1500 km (as an upper limit; instead 1150 km). Table 3a for a single patch antenna on the satellite board shows that the required power P_{sat} increases with the bandwidth and with the altitude; we can see that the requirements for E_b/N_0 and margin M are not satisfied for some cases (last row – small or even negative margin is available).

Satisfying results have been obtained for 2 or 4 patch antennas in the X-band – see results in Table 3*b* for altitudes 600 and 1500 km. The antennas have been selected with appropriate gain and beamwidth; if the antenna gain increases, the required transmitted power from the satellite definitely decreases even for 1500-km orbit altitude (which falls into the inner Van-Allen radiation belt).

Let's finally evaluate the data-transfer throughput in the X band along the DL channel from a single CubeSat. The simplified analysis for low-altitude orbits (e.g. ~600 km altitude and ~84 deg inclination) shows that the single satellite will pass over a fixed ground station typically once daily. If we use a single patch antenna with ~60 deg 3-dB beamwidth (or ~500-km wide communication "track" over the Earth surface), the satellite will be "visible" for high-speed data transfer over a given Earth station (bit rate r_b ~ 30-60 Mbps for QPSK modulation; P_{sat} = 0.24, P_{GS} = 2.3 W) for ~2-3 min. This is a small LoS period, but if we use switchable 4-patch antenna (P_{sat} = 50 mW, P_{GS} = 490 mW), this period could increase up to 8-9 min with average r_b ~ $0.35r_{b,max}$ (see the considerations in our papers [51], where we propose a concept for prolonged communication sessions between the small satellite and the Earth station). This value can increase at higher P_{sat}. Therefore, the total data volume for a single communication session is evaluated at no less than 10 Gb for one shared DL channel. This is fully enough (according to us) for reliable maintenance of the proposed project for gamma-ray monitoring by CubeSats in swarms as their secondary function together with the implementation of the communication data transfer defined by the primary function of these swarms (broadband fast Internet delivery). At higher-altitude orbit (e.g. 1500 km) the bit rate decrease with more than 6 times, but remains relatively big.

Of course, it is not a good idea each satellite from the swarm separately to communicate with the ground station for transfer of the accumulated data from the gamma-ray detector during an orbital tour around the Earth globe. As we proposed in [37], the ordinary members of the swarm (slave satellites) can communicate and send the accumulated (and even post-processed) data to a master satellite by the established inter-satellite swarm connections; in this case, only the master satellite will be responsible for the data transfer to the Earth station (meanwhile, the master satellite can have capabilities for additional onboard processing of the data from the gamma-ray detection and to reduce considerable the volume of these data). In all cases, when the swarm members' relations are based on the principle of "master-slave" satellites, the data throughput will increase, and the master satellite can use specially dedicated channel for the accumulated data from the gamma-ray monitoring of the whole swarm.

6. CONCLUSIONS

In this paper, we made a bold proposition to use the future satellite swarms (e.g. like in the Starlink project) with primary function for a broadband Internet delivery from the near space to perform a secondary common function – a collection of data from online gamma-ray observation of the deep space. In the last several years the small satellites have successfully taken the responsibility for performing important tasks in the gamma-ray astronomy, even as well-equipped single gamma-ray telescopes. If they have been designed to work as satellite constellation in concert, even several gamma-ray telescopes can "cover" the whole space around the Earth. Our proposal is going beyond. If the planned for implementation thousands of small satellites operating as large swarms for implementation of new communication technology for fast broadband Internet access from the space for millions of ground users, the swarm members can share together a relatively passive gamma-ray detection as a new secondary function. For this aim, each swarm member has to be equipped by a simple gamma-ray detector with enough sensitivity and small energy consumption and weight, simple installed software to control the detector and to ensure sending of the accumulated data for future post-processing in a swarm command centre. This proposal is very similar to the already working project for ultra-high energy cosmic rays detection by the optical cameras of millions of smartphones on the Earth surface and both of them have a lot of common issues; the main benefit of the swarm observation is that the detectors on the satellites on LEO orbits can detect gamma-ray radiation with considerable smaller energy – MeV and even hundreds of keV, which is impossible from the Earth.

We have shown in this paper, that the accumulated data from a single gamma-ray detector will not exceed a reasonable volume (several Gb per day as an upper limit without any onboard post-processing) and their transmission to the Earth station will not considerably disturb the primary communication session along the downlink channel of the satellite swarm members (the needed speed is less than 0.16 Mbps on the background of the proposed hundreds Mbps data rate for the next-generation Internet delivery from the space). If the registered data are collected in the frame of the swarm in the space, a master satellite from the swarm should have the responsibility to send the collected and preliminary processed data to a selected ground station within dedicated communication sessions in a fixed time period.

The proposed idea for online gamma-ray monitoring of the deep space from small satellites in a large swarm is still raw. The idea will be developed in concrete frames in the next our publications.

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REFERENCES

[1] J.C. Chancellor, G. B. Scott, and J. P. Sutton (2014), “Space Radiation: The Number One Risk to Astronaut Health beyond Low Earth Orbit”, Life (Basel) ISSN 2075-1729, pp. 491–510, https://doi.org/10.3390/life4030491

[2] F. Cortese et. al. (2018), “Vive la radiorésistance!: converging research in radiobiology and biogerontology to enhance human radioresistance for deep space exploration and colonization”, Oncotarget, Vol. 9, (No. 18), pp. 14692-14722

[3] D. Sinclair, J. Dyer (2013), “Radiation Effects and COTS Parts in SmallSats”, Proc. AIAA/ USU Conference on Small Satellites, Mission Lessons, SSC13-IV-3.

[4] “State of the Art of Small Spacecraft Technology” (2018), NASA/TP—2018–220027, NASA Ames Research Center, Small Spacecraft Systems Virtual Institute, Moffett Field, California, ed. by Sasha Weston, online available: https://sst-soa.arc.nasa.gov/

[5] Liz Hays (2013), "Space-based Gamma-ray Astronomy”, Fermi Summer School 2013, online available: https://fermi.gsfc.nasa.gov/science/mtgs/summerschool/2013/program.html

[6] R. Diehl (2015), “Cosmic Gamma-Ray Spectroscopy”, Astronomical Review, Vol. 8, Issue 2, https://doi.org/10.1080/21672857.2013.11519720

[7] R. Diehl, N. Prantzos, and P. von Ballmoos (2006), “Astrophysical constraints from gamma-ray spectroscopy”, Nuclear Physics A, 777:70-97, Oct. 2006

[8] R. Ramaty, B. Kozlovsky, and R. E. Lingenfelter (1979), “Nuclear gamma-rays from energetic particle interactions”, ApJS, 40:487-526, July 1979.

[9] N. Prantzos, C. Boehm, A. M. Bykov, et al. (2011), “The 511 keV emission from positron annihilation in the Galaxy”, Reviews of Modern Physics, 83, 1001-1056, July 2011

[10] B. Gendre, G. Stratta,J.L. Atteia, S. Basa, M. Boër, D.M. Coward, S. Cutini, V. d'Elia, E.J. Howell, A. Klotz, L. Piro (2013), "The Ultra-Long Gamma-Ray Burst 111209A: The Collapse of a Blue Supergiant?", Astrophysical Journal, 766 (1), doi:10.1088/0004-637X/766/1/30.30.

[11] Small Satellites: Regulatory Challenges and Chances, edited by I. Marboe, Ch. 12: The ITU Radio Regulations Related to Small Satellites, by A. Matas, Y. Henry and Ch. Ch. Loo, Brill Nijhof Laiden (2016) ISBN 978-90-04-31223-4; pp. 237-264

[12] M. Gachev, and P. Dankov (2016), “Low-Profile Tracking Ground-Station Antenna Arrays for Satellite Communications”, 7th Nano-Satellite Symposium, Varna, October 2016, online available: https://www.researchgate.net/publication/311824833_Low_Profile_Tracking_Ground-Station_Antenna_Arrays_for_Satellite_Communications/citations

[13] NASA Compton Gamma-Ray Observatory (updated 2018), NSSDCA/COSPAR ID: 1991-027B, online available: https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1991-027B

[14] M. Su, T.R. Slatyer, D.P. Finkbeiner (2010), "Giant Gamma-ray Bubbles from Fermi-LAT: Active Galactic Nucleus Activity or Bipolar Galactic Wind?", Astrophysical Journal, 724 (2): 1044-1082. doi:10.1088/0004-637X/724/2/1044

[15] "Fermi's Latest Gamma-ray Census Highlights Cosmic Mysteries", NASA, Sept 2011, online available: https://www.nasa.gov/mission_pages/GLAST/news/gamma-ray-census.html

[16] "The largest catalog ever published of very high-energy gamma ray sources in the Galaxy", CNRS, April 9, 2018, https://phys.org/news/2018-04-largest-published-high-energy-gamma-ray.html

[17] Fermi Sees Gamma Rays from Far Side Solar Flares https://www.youtube.com/watch?v=BdTTSylIHYQ

[18] E. L. Shkolnik (2018), “On the verge of an astronomy CubeSat revolution”, Nature Astronomy, vol. 2, May 2018, pp. 374-378, www.nature.com/natureastronomy

[19] M. Knapp, S. Seager (2015),”ASTERIA: A CubeSat for exoplanet transit and stellar photo-metry”, ESS/AAS Meeting 3 106.08 (Am. Astronom. Soc.; https://aas.org/)

[20] PicSat mission website, https://picsat.obspm.fr/

[21] P. Kaaret (2017), “HaloSat – a CubeSat to study the hot galactic halo”, Am. Astronom. Soc. Meeting 328.03 (2017), http://adsabs.harvard.edu/abs/2017AAS...22932803K

[22] B. T. Fleming et al. (2017), “The Colorado Ultraviolet Transit Experiment (CUTE): a dedicated cubesat mission for the study of exoplanetary mass loss and magnetic fields”, SPIE Conf. Series, Vol. 10397 (SPIE, 2017), https://arxiv.org/pdf/1801.02673.pdf

[23] E. Shkolnik, et al. (2017), “Monitoring the high-energy radiation environment of exoplanets around low-mass stars with SPARCS (star-planet activity research CubeSat)”, Astrobiol. Sci. Conf. 2017 1965; http://adsabs.harvard.edu/abs/2018AAS...23122804S

[24] J. Racusin, et al. (2017), “BurstCube: a CubeSat for gravitational wave counterparts”, Preprint at https://arxiv.org/abs/1708.09292 (2017).

[25] D. Whiteson, M. Mulhearn, C. Shimmin, K. Cranmer, K. Brodie, D. Burns (2016), “Searching for ultra-high energy cosmic rays with smartphones”, Astroparticle Physics, 79 (2016) pp. 1-9,

https://doi.org/10.1016/j.astropartphys.2016.02.002
[26] CRAYFIS project, https://crayfis.io/
[27] I. Levchenko, M. Keidar, J. Cantrell, Y.-L. Wu, H. Kuninaka, K. Bazaka, S. Xu “Explore space using swarms of tiny satellites”, Nature, vol. 562, 11 Oct. 2018, pp. 185-187
[28] D. Messier (2014), "Is Google Planning Son of Teledesic?", Parabolic Arc., 2014-06-14
[29] OneWeb site: https://www.oneweb.world/
[30] S. Clark (2019), "First six OneWeb satellites launched from French Guiana", Spaceflight Now; retrieved 2019-03-04
[31] P. B. de Selding (2015), "OneWeb Taps Airbus To Build 900 Internet Smallsats", SpaceNews, 2015-06-15, retrieved 19 June 2015
[32] SpaceX's site: https://www.spacex.com/
[33] Starlink: https://en.wikipedia.org/wiki/Starlink_(satellite_constellation)#cite_note-announcementEvent-6
[34] SpaceX Seattle 2015: https://www.youtube.com/watch?v=AHeZHyOnsm4
[35] https://www.starlink.com/
[36] M. Wall (2019), “Elon Musk Says It's 'So Far, So Good' for SpaceX's 1st 60 Starlink Satellites”, https://www.space.com/elon-musk-says-spacex-starlink-satellites-doing-well.html
[37] S. Ivanov, B. Konstantinov, S. Tzokov, T. Ivanov, T. Kanev, V. Zlateva, M. Avramov, B. Ivanov, N. Neshev, V. Vassilev, O. Ognyanov, and P. Dankov (2017), “Space Debris Identification, Classification and Aggregation with Optimized Satellite Swarms”, in Innovative Ideas for Micro/Nano-Satellite Mission, edited by R. Sandau, R. Kawashima, S. Nakasuka, J. J. Sellers, IAA Publ., International Academy of Austronautics, Book Series; ISBN 978-2-917761-28-1, vol. 4
[38] N. Neshev, B. Ivanov, E. Nesheva, T. Kanev, and P. Dankov (2015),"Conceptual Applicability of Flexible Small Satellite Swarm (SSS) Formations in Meteoroid Defense and Debris Removal", Plan the European Roadmap and its Activities for Space Exploitation of Robotics and Autonomy, Noordwijkerout, The Netherlands, 11-12 February 2015 (online) http://robotics.estec.esa.int/h2020-peraspera/node/15
[39] W.T. Vestrand, D.J. Forrest, K.A. Levenson, C. Whitfordz, D. Fletcher-Holmesz, A. Wellsz, and A. Owens (1999), “CATSAT: A Small Satellite for Studying Gamma-Ray Bursts”, AIP Conference Proceedings, Dec. 1999, DOI: 10.1063/1.1302231
[40] A Meuris (2014), “Semiconductor detector developments for high energy space astronomy”, IOP Publishing Ltd., Journal of Instrumentation, Volume 9, May 2014
[41] J. DeLange, S. Frick, J. Runnels, D. Gebre-Egziabher, K. Hedstrom (2016), “Sensor for Small Satellite Relative PNT in Deep-Space”, 2016 IEEE/ION Position, Location and Navigation Symposium (PLANS), 11-14 April 2016, Savannah, GA, USA DOI: 10.1109/PLANS.2016.7479794
[42] Q. G. Schiller, A. Mahendrakumar, X. Li (2010), “REPTile: A Miniaturized Detector for a CubeSat Mission to Measure Relativistic Particles in Near-Earth Space”, 24th Annual AIAA/USU Conf. on Small Sats, Aug. 2010, Logan, UT, USA, SSC10-VIII-1
[43] E. Kalemci, E. Ümit, R. Aslan, (2013), “X-ray detector on 2U Cubesat BeEagleSAT of QB50”, 6th Int. Conf. on Recent Advances in Space Technologies (RAST), 12-14 June 2013, Istanbul, Turkey, DOI: 10.1109/RAST.2013.6581341
[44] S. Zhu, F. Kondev, M. Carpenter, I. Ahmad, C. Chiara, J. Greene, G. Gurdal, R. Janssens, S. Lalkovski, T. Lauritsen, et al. (2011), Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 652, 231 (2011), ISSN 01689002.
[45] I. Iliev, P. Dankov (2018), “Distance Methods for Gamma Mapping with Unmanned Aerial Vehicles (UAV)” (in Bulgarian), Annuaire de l’Université de Sofia “St. Kliment Ohridski”, Faculté de Physique, v. 109, 2018 (online available)
[46] G. F. Knoll (1999), “Radiation Detection and Measurement”, Wiley & Sons, New York, 1999
[47] O. Montenbruck (2003), “Kinematic GPS positioning of LEO satellites using ionosphere-free single frequency measurements”, Aerospace Science and Technology 7 (2003) 396–405
[48] M. Gachev (2007), “Satellite Communications”, Heron press, ISBN 978-954954954-580-223-0 (2007)
[49] ITU-R, Amateur and amateur-satellite services, Ch.3 „Amateur-satellite services“ (2008); online available: http://www.itu.int/en/ITU-R/space/AmateurDoc/AmateurSatServiceFreq.pdf
[50] J. A. King, J. Ness, G. Bonin, M. Brett, D. Faber (2012), “Nanosat Ka-Band Communications - A Paradigm Shift in Small Satellite Data Throughput”, 26th Annual AIAA/USU Conf. on Small Satellites, Logan, Utah USA, Aug. 2012
[51] P. Dankov, M. Gachev, V. Vassilev, K. Zlatkov, Z. Kiss'ovski, D. Mateev, O. Ognyanov, I. Krassimirov, C. Simeonov (2013), "Small Satellite Mission in Support of the Science Expeditions' Activities of in the Antarctic”, in "Innovative Ideas for Micro/Nano-Satellite Mission", edited by R. Sandau, R. Kawashima, S. Nakasuka, J. J. Sellers, IAA Publ., International Academy of Austronautics, Book Series, ISBN 978-2-917761-28-1, Tokyo, Japan, vol. 1, No. 3 pp. 88-100